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Role of topography-induced gravitational stresses in basin inversion: The case study of the Pannonian basin

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Abstract. Numerical stress models suggest that gravitational body forces associated with elevated topography around sedimentary basins can significantly influence the stress and strain pattern in basin interiors. In the absence of tectonic forces, basins surrounded by high-altitude mountain ranges experience net horizontal compression. Owing to gravitational forces pointing from areas of high gravitational potential energy to subsided basin areas, further lithospheric extension can eventually terminate, leading to a gradual late stage inversion of the entire basin system. Modeling results suggest that the state of recent stress in the Pannonian basin, particularly in its western part, is controlled by the interplay of plate boundary forces, i.e., the counterclockwise rotation and northward indentation of the Adriatic microplate against the Alpine-Dinaric belt, and buoyancy forces associated with the elevated topography and related crustal thickness variation of the Alpine-Dinaric belt. Model calculations show that uplifted regions surrounding the basin system can exert compression on the thinned Pannonian lithosphere of ~40-60 MPa that is of the order of the assumed far-field tectonic stress magnitudes. The combined analysis of stress sources of tectonic and gravitational origin helps estimating the magnitude of maximum horizontal compression. High levels of compressional stresses (up to >100 MPa) are concentrated in the elastic core of the lithosphere, consistent with the ongoing structural inversion of the Pannonian basin system.

1. Introduction

Sedimentary basins are often subjects to episodic changes in tectonic regime. Spatial and temporal fluctuations in the stress field have important consequences for the evolution of the basin architecture and stratigraphic pattern. Intraplate stresses can modulate basin geometry, induce rapid differential vertical motions, influence sedimentation rates, and affect fluid flow systems [e.g., *Cloetingh et al.,* 1985, 1989; *Kooi and Cloetingh,* 1989; *van Balen et al.,* 1999]. Structural inversion of sedimentary basins occurs generally in intraplate areas (e.g., Polish trough) or in back arc setting (e.g., Sunda arc). It is widely recognized that deformation of inverted basins is controlled by compressional stress regimes. Basin inversion is related to changes in the regional stress field from tension, which conducts basin formation and subsidence, to compression, which results in contraction and flexure of the lithosphere associated with differential vertical movements. This process is often characterized by a short time interval between extensional and compressional phases [*Cooper and Williams,* 1989]. The extended, hot, and hence weak lithosphere underlying sedimentary basins is prone to reactivation under relatively low compressional stresses. Extensional basin formation is an inherently weakening process of the lithosphere, allowing subsequent deformation to be localized beneath earlier formed basin. Inversion tectonics has received great interest in hydrocarbon industry because of the significance of positive structural inversion in the process of hydrocarbon generation, migration, and trapping. It is well known that uplift of a hydrocarbon-prone area generally reduces the prospecting depth window and leads to erosion. In contrast, rapid basin subsidence can increase seal integrity and hydrocarbon expulsion.

The style and degree of basin inversion depend on the mechanical strength of the deforming lithosphere and the state of stress induced by the interaction of extrinsic (plate boundary) and intrinsic (intraplate body) forces. The international World Map Stress project [*Zoback,* 1992] demonstrated the presence of broad provinces characterized by fairly homogeneous stress field. It was suggested that large-scale tectonic forces are the primary controlling factors of the observed stress pattern. Plate boundary forces have been long considered to play dominant role and are thought to be directly responsible for driving plate motions [e.g., *Forsyth and Uyeda,* 1975; *Richardson et al.,* 1979; *Wortel et al.,* 1991]. Similarly, these forces play a key role in the deformation history of sedimentary basins because tectonic stresses can cause short-term deviations from long-term patterns of thermal subsidence [*Cloetingh et al.,* 1989]. The accelerated late stage (Plio-Pleistocene) subsidence of the North Sea basin and uplift of the surrounding areas are considered to be in response to the buildup of intraplate compressional stresses in NW Europe [*van Wees and Cloetingh,* 1996]. The interplay of the Atlantic ridge-push forces from the northwest and collisional forces associated with the ongoing Alpine orogeny in the south [*Gölke and Coblentz,* 1996] produces the well-established western European stress province [*Müller et al.,* 1992]. The frequent late Mesozoic through Cenozoic inversional reactivation of the Atlantic passive margin was observed in several subbasins [e.g., *Cloetingh et al.,* 1990; *Gabrielsen et al.,* 1997; *Boldreel and Andersen,* 1998].

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It has been obvious that large-scale deformation processes can significantly alter the density distribution through crustal and lithospheric thinning or thickening and corresponding changes in surface elevation. Lateral density variation in the lithosphere is associated with changes in gravitational potential energy, and in addition to plate boundary forces, it has long been recognized as a primary source of intraplate stress, especially in zones of active orogeny [*Artyushkov*, 1973; *Fleitout and Froidevaux*, 1982; *Molnar and Lyon-Caen*, 1988; *Sonder*, 1990; *Bott*, 1993; *Jones et al.*, 1996]. The stress field in sedimentary basins surrounded by or adjacent to a mountain belt can be effectively influenced by gravitational forces. This aspect of basin inversion mechanisms has been neglected but can be particularly relevant in the case of the Mediterranean system of back arc basins, which are superimposed on former orogenic terrains and hence are typically surrounded by elevated orogenic belts. Although several numerical modeling and analytical studies addressed the role of gravitational stresses in geodynamic processes, so far little attention has been paid to the investigation of the interaction and relative importance of intraplate and plate boundary forces. Nevertheless, finite element stress modeling [*Richardson and Coblentz*, 1994; *Gölke and Coblentz*, 1996] demonstrated that the calculation of stresses associated with topography variation and related Moho depth changes allows making estimates on the magnitude of either the ill-constrained tectonic forces or the average values of lithospheric stress.

The principal aim of the present study is twofold. First, after reviewing the concept of gravitational stresses and introducing the late stage inversion of the Pannonian basin, an attempt is made to quantitatively evaluate the effect of gravitational forces on the stress pattern of an intramountain sedimentary basin. Model calculations evaluate the effect of forces related to the presence of an uplifted plateau on the stress pattern of a neighboring basin. Then, building on this concept, the sources of recent tectonic stress in the Pannonian basin is investigated. This basin has reached an advanced stage of evolution with respect to other Mediterranean basins. Contemporary stress data, seismicity pattern, seismic profiles, and the Quaternary subsidence history indicate that the back arc type Pannonian basin is in the period of structural inversion [*Horváth*, 1995; *Horváth and Cloetingh*, 1996; *Bada et al.*, 1999; *Gerner et al.*, 1999]. It has been suggested that an increase of horizontal compression due to the changes of boundary conditions around the basin system causes buckling of the whole Pannonian lithosphere [cf. *Horváth and Cloetingh*, 1996]. In order to improve our understanding of the recent tectonics in the Pannonian basin and to test the importance of gravitational stresses in basin inversion a modeling study has been undertaken. Numerical models have been used to simulate the combined effect of plate boundary forces and intraplate gravitational stresses. An attempt has been made to quantify these tectonic processes in terms of force magnitudes and to estimate the mean level of horizontal tectonic stresses. Consequently, the principal aim of the present study is to analyze the interaction between tectonic and buoyancy forces in an intra-mountain basin. This is then applied to arrive at a better knowledge on the origin and magnitude of the state of contemporary stress in the Pannonian basin. Since the recent stress and strain pattern in the eastern region of the study area is not yet well understood, the primary focus of this study is put on the western parts of the Pannonian basin.

2. Stresses Due to Density Variation in the Lithosphere

Among various intraplate stress sources (e.g., membrane, thermal, and flexural stresses), the most essential appears to be the lateral and vertical density variations in the lithosphere. The frequent coexistence of compressional and tensional stresses in a short distance suggests that gravitational forces are comparable in magnitude with plate boundary forces [*Fleitout and Froidevaux*, 1983]. Since the pioneering work of *Artyushkov* [1973], numerous analytical and modeling studies addressed the problem of how mass heterogeneities in the lithosphere can influence the state of stress from local to platewide scale [e.g., *Lister*, 1975; *Dahlen*, 1981; *Fleitout and Froidevaux*, 1982; *Sonder*, 1990; *Bird*, 1991; *Ranalli*, 1992; *Coblentz et al.*, 1994; *Jones et al.*, 1996]. One approach to describe the effect of mass heterogeneities was proposed by

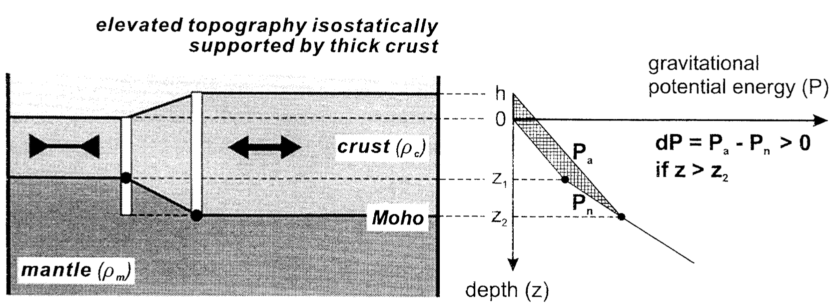

Figure 1. Changes of gravitational potential energy due to lateral density variations associated with topography and crustal thickness changes. Elevated topography is compensated at the bottom of the thickened crust ($z = z_2$). The highland area is characterized by an excess of potential energy with respect to the lowland region. This can result in the development of extension in the uplifted area. As a consequence, compression can occur in the lowland crust, which is increased if the effected area is a sedimentary basin with attenuated crust [modified after *Bird*, 1991]. Here ρ_c and ρ_m are the density of the crust and the mantle lithosphere, respectively.

Fleitout and Froidevaux [1982]. They use the concept of density moment assuming local isostatic compensation. The product of the magnitude and depth of density anomalies characterizes their capacity to give rise to lithospheric deformation. This method is applicable provided the lateral size of the density anomaly is large compared to the thickness of the lithosphere.

Another approach uses the concept of gravitational potential energy P [*Molnar and Lyon-Caen,* 1988; *Bird,* 1991; *Coblentz et al.,* 1994; *Jones et al.,* 1996]. Lateral and vertical density anomalies produce lateral variation in the potential energy of the lithosphere. These changes can be directly related to either the local or the platewide state of stress field. Regions of tension and compression can be inferred by looking at the difference between the potential energy above compensation depth of an anomalous lithospheric column P_a and a reference lithospheric column P_n [*Coblentz et al.,* 1994]. In general, a lithospheric column with negative potential energy contrast (P_a-P_n<0) will generate compression in the anomalous lithosphere. A good example is given when the mantle lithosphere is thickened. Such lithospheric roots can induce net compression that is capable of sustaining mountain building without the need of far-field forces [*Fleitout and Froidevaux,* 1982]. In contrast, an increase of crustal thickness leads to isostatic uplift, excess potential energy (P_a-P_n>0) and net tension in the thickened crust (Figure 1). In such settings, lithospheric material tends to flow vertically and horizontally in order to reach equilibrium of potential energies. In other words, the crust in mountain belts can extend under their own weight, and material transport occurs from high to low regions. Such sideway tectonic transport is called extensional collapse of orogens [cf. *Dewey,* 1988]. Actual examples are numerous, e.g., the Himalayan/Tibetean orogen [*England and Houseman,* 1989], western United States [*Jones et al.,* 1996], and the Andes [*Richardson and Coblentz,* 1994]. The formation of the Late Cretaceous Gosau-type extensional basins in the Eastern Alps was controlled by similar processes [*Willingshofer et al.,* 1999]. In general, active orogenic belts with thickened and, owing to the synorogenic increase of the heat flow, weakened crusts are preferential sites for subsequent extension. Collapse of orogenic terrains is induced by gravitational forces enhanced by sharp elevation gradients. Direction of horizontal tension is aligned with the gradient in potential energy and hence with the gradient of topography and bathimetry. A deficiency of the potential energy is typical for regions of subsidence. Subsidence of a few kilometers can cause a considerable reduction of gravitational potential energy. This decrease can result in significant compressional stresses in the crust [e.g., *Jones et al.,* 1996]. To date, the quantitative analysis of these stresses have been overlooked in basin evolution studies, particularly in back arc type (or intramountain) basins, where an area of subsidence is usually surrounded by an elevated mountain arc.

In collisional belts both the crust and the mantle lithosphere can be thickened considerably, and their effects would be competing with one another. In such a setting, the local lithospheric configuration of mountain belts can vary and result in alternating stress patterns both horizontally and vertically [*Bott,* 1990]. In addition, the detachment of the dense lithospheric root from beneath orogens can also lead to late stage tectonic inversion, i.e., rapid uplift and extension, observed in many orogenic belts [e.g., *Sonder et al.,* 1987; *Ranalli et al.,* 1989]. Similar spatial and temporal variation of the stress pattern is also an inherent feature of extensional basin development. Attenuation and subsidence of the crust gradually lead to mass defects and a decrease of the gravitational potential energy, which give rise to crustal compression. At the same time, elevation of the mantle lithosphere and updoming of the asthenosphere lead to mass surplus and an increase of the potential energy, which give rise to extension in the subcrustal domain of the extensional basin. This "ridge" or "rift" push force is a transient feature, as it permanently decreases with the progress of thermal cooling. However, the crustal compression remains constant and efficient until the crustal structure remains unchanged. Most recently, a detailed analysis of the ridge (rift) push force and convective instability of the elevated asthenosphere has been performed [*Huismans,* 1999]. In this paper we evaluate the stress field generated by the crustal contrast between a mountain range (highland) and an intramountain basin (lowland).

3. Modeling Location: The Pannonian Basin

3.1. Tectonic Setting

The study area, the Pannonian basin and surrounding orogens, is located in the northern part of the Mediterranean region. The Cenozoic evolution of the area has been principally controlled by the convergence of the African and European plates and the indentation of the Adriatic (Apulian) microplate against Europe. An important feature in this overall compressional setting is the abundance of extensional basins superimposed on former orogenic terrains and often associated with lateral displacement of crustal blocks (escape structures) (Figure 2). These basins are all located in the vicinity of a once active subduction zone, which suggests a genetic relationship. Ongoing extension is observed behind actively retreating subduction zones (Aegean basin/Hellenic arc and Tyrrhenian basin/Calabrian arc), whereas extension considerably diminished or terminated in areas where retreat of the subducted slab ceased (Pannonian basin/Carpathian arc).

The formation of the back arc type Pannonian basin system [*Royden and Horváth,* 1988] began during the late early Miocene. This extensional basin evolved in the overall compressional setting of the Alpine-Carpathian orogenic realm. The synrift phase of basin development finished during the middle Miocene, while the postrift phase, characterized by rapid and substantial thermal subsidence and gradual infilling of the Pannonian basin, terminated in the early Pliocene (Figure 3). The postrift period was interrupted by two important compressional events [*Horváth,* 1995]. One transitional event took place during the earliest late Miocene (Sarmatian/Pannonian boundary on the central Paratethys time chart), giving rise to fault reactivation and structural inversion on a local scale. The second, more profound compressional phase, which started during the Pliocene and continued until recent times, resulted in the complete termination of extension in the whole Pannonian basin. This

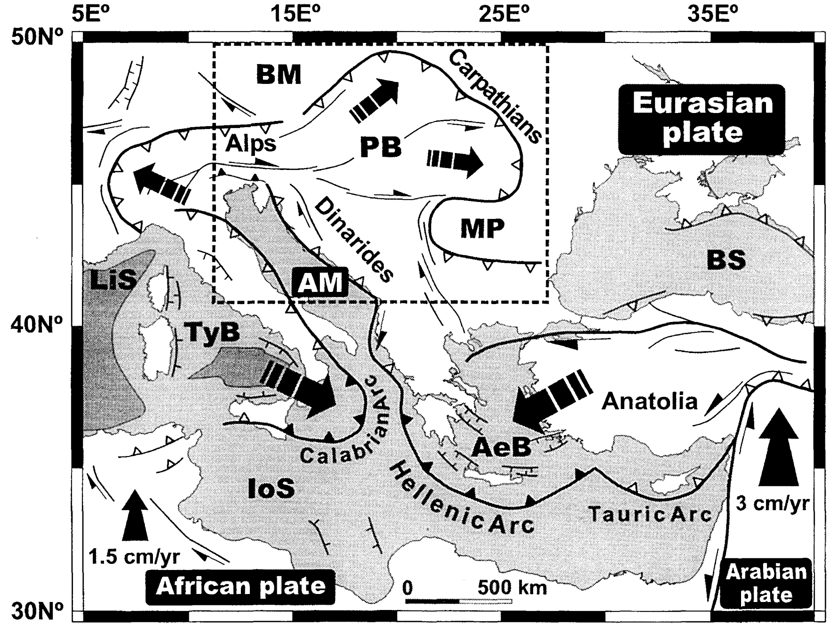

Figure 2. Simplified tectonic map of the central and eastern Mediterranean region. Active extension is observed behind retreating trench zones (Calabrian and Hellenic arcs, marked by solid triangles), whereas structural inversion is in progress in areas behind inactive belts of subduction or collision (e.g., Alpine, Carpathian, and Dinaric arcs, marked by open triangles). Arrows indicate late Cenozoic translation and rotation of various microplates and crustal blocks. Dotted line marks the study area shown in Figure 4. AeB, Aegean back arc basin; AM, Adriatic microplate; BS, Black Sea; BM, Bohemian Massif; IoS, Ionian Sea; LiS, Ligurian Sea; MP, Moesian Platform; PB, Pannonian basin; TyB, Tyrrhenian back arc basin.

process is assumed to be the consequence of changing boundary conditions along the Carpathian arc, i.e., the complete consumption of the subductable lithosphere of the European foreland [*Horváth,* 1993]. As a result, the recent buildup of intraplate compressional stresses caused basin-scale buckling of the Pannonian lithosphere associated with late stage subsidence anomalies, i.e., accelerated subsidence and uplift in the central and peripheral areas, respectively [*Horváth and Cloetingh,* 1996].

The late stage evolution of the basin has been controlled primarily by a stress field generated by the collision of the Adriatic block with the Dinarides [*Bada et al.,* 1998]. The topographic features in the region (Figure 4) well reflect the main characteristics of the Miocene through Quaternary evolution of this segment of the Alpine-Mediterranean region. The topographically low Pannonian basin is completely surrounded by fold-and-thrust belts of various altitudes. The highest summits are found in the western mountains: the elevation of the eastern Alps locally reaches >3500 m. The Dinarides exceed 2000 m in the southeast near Albania. The average altitude of the curving Carpathian arc is in the range of 1000-1500 m with peaks reaching the heights of >2500 m.

3.2. Contemporary Stress and Strain Pattern

The Mediterranean region exhibits a complicated pattern of contemporaneous tectonic stress [*Müller et al.,* 1992; *Philip,* 1987; *Rebaï et al.,* 1992]. For instance, tension in and around the Aegean and Tyrrhenian Seas and compression in the Alpine and Dinaric chain reflect a short-scale variation of the stress field. *Rebaï et al.* [1992] were among the first to suggest that no indication of active extension can be observed inside the Pannonian basin. Instead, the intra-Carpathian area is characterized by either strike-slip or thrust faulting. Great complexity of the stress field has been found in the Pannonian region where a comprehensive database of various stress indicators has been compiled [*Gerner et al.,* 1999]. Using an updated version of this database containing >400 entries, the primary features of the state of present-day stress are summarized (Figure 5). The region can be subdivided into distinct areas where the maximum horizontal stress orientations S_{Hmax} reveal good consistency. S_{Hmax} directions show a clockwise rotation along the actively deforming South Alpine-Dinaric front. N-S to NNW-SSE directed compression in the Southern and Eastern Alps gradually becomes NE-SW oriented along the southern coast of the Adriatic Sea. This pattern is further traceable in the southern sectors of the Pannonian basin, while the interior area is characterized by a dominantly NE-SW orientation. Closer to the eastern parts of the Carpathian chain, S_{Hmax} directions are progressively changing to E-W. Farther to the east, in the seismically active Vrancea zone in the eastern Carpathians, the observed S_{Hmax} orientation is dominantly NW-SE. In the easternmost parts of the eastern Alps and western sectors of the Pannonian basin, stress measurements yielded a S_{Hmax} pattern with NE-SW to E-W directions. Finally, sparse data from the northern segment of the Carpathian arc indicate NW-SE to N-S

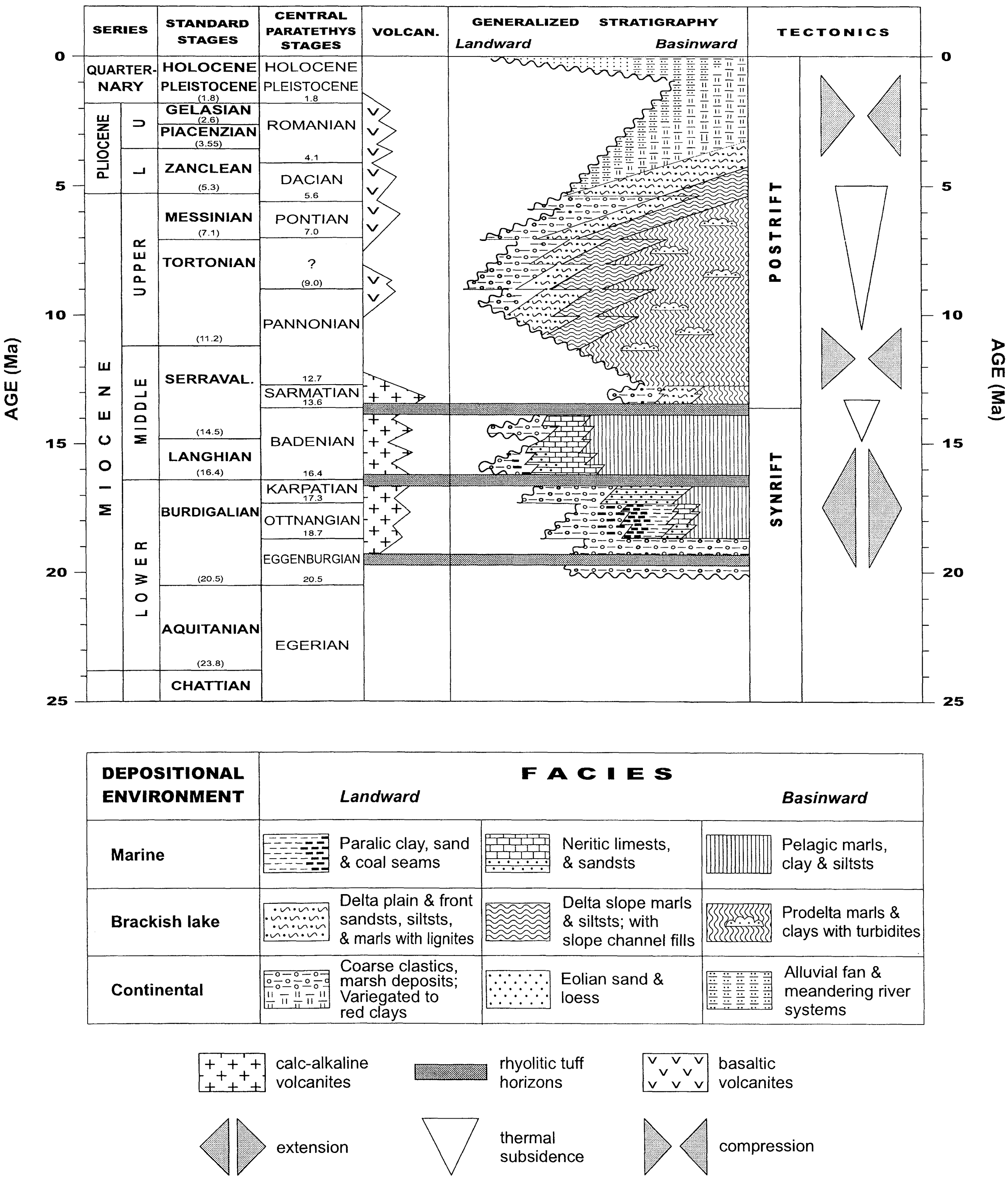

Figure 3. Evolutionary scheme of the Pannonian basin with major volcanic horizons and events, generalized stratigraphy, and main tectonic phases. The primary depositional environments and facies of the Pannonian basin are described in the bottom panel [modified after *Horváth and Tari,* 1999].

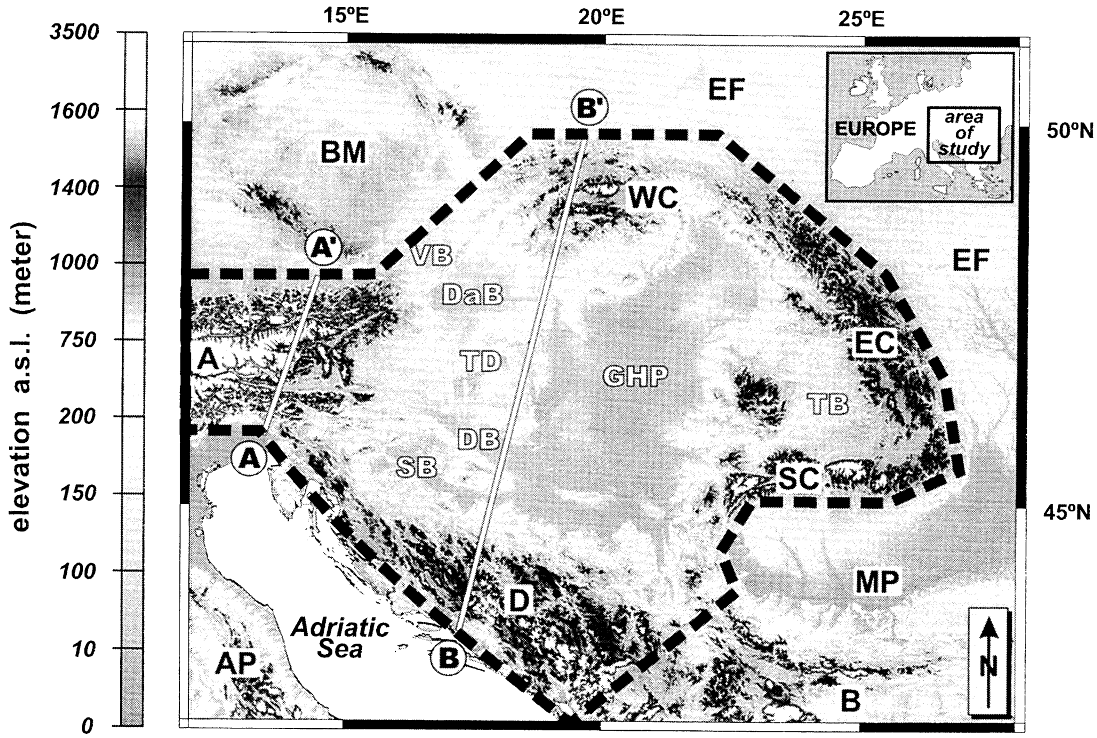

Figure 4. Shaded relief map showing the main topographic features in the Pannonian basin and neighboring orogens. The low elevation and flat-lying intra-Carpathian area is surrounded by mountain belts with elevation maximums of ~2500 m (Carpathians) up to ~3500 m (eastern Alps). Thick dashed line indicates the boundaries of the finite element model employed for numerical modeling. Lines A-A' and B-B' show the location of the sections along which stress magnitude calculation was carried out (see Figure 15). A, eastern Alps; AP, Apennines; B, Balkanides; BM, Bohemian Massif; EC, SC, and WC, eastern, southern, and western Carpathians, respectively; D, Dinarides; DaB, Danube basin; DB, Drava basin; EF, European foreland; GHP, Great Hungarian Plain; MP, Moesian Platform; SB, Sava basin; TB, Transylvanian basin; TD, Transdanubia; VB, Vienna basin.

directed compression being roughly perpendicular to the strike of the mountain belt.

Since the majority of stress measurement techniques yield only the direction of the horizontal stress axes, it is the earthquake focal mechanism data which help to determine the type of the stress regime. In the Pannonian basin [*Gerner et al.,* 1999], focal mechanisms suggest the dominance of strike-slip to thrust faulting along mainly preexisting zones of weakness in the upper crustal levels. The nearly complete lack of normal faulting is striking (Figure 6). Consequently, we can conclude that crustal extension of the Pannonian basin has been terminated. A new tectonic regime prevails: the structural inversion of the Pannonian basin is in progress. The three-dimensional geometry of the subsiding and uplifting areas and the subsidence history of the basin system argue for a large-scale deflection of the Pannonian lithosphere. This deformation was suggested to be the consequence of the Late Pliocene through Quaternary buildup of intraplate compressive stresses in the Pannonian region [*Horváth and Cloetingh,* 1996; *Cloetingh et al.,* 1999].

The Pannonian basin and neighboring orogens exhibit a seismicity pattern with remarkable differences in various tectonic units. The earthquake database of the region contains a record of ~4500 events for the time period of 456 to 1998 [*Gerner et al.,* 1999; *Tóth et al.,* 2001]. Hypocenters are restricted to the crust in the whole region (Figure 7), with only the exception of the Vrancea zone in the eastern Carpathians. In the Pannonian region, crustal events are characterized by low- to medium-level activity. Earthquake data show, however, that intense deformation is taking place in the western and southern part of the basin system. In the Vrancea zone the vertical distribution of events indicates a well-defined, nearly vertical lithospheric slab [*Oncescu,* 1984; *Wenzel et al.,* 1998]. Medium- to high-level of activity is characteristic for both the crustal and mantle part of the lithosphere, while a well-defined seismic gap exists between the depths of 40 and 70 km. The clear separation of crustal and mantle earthquake activity and the results of seismic tomography [*Wortel and Spakman,* 1992] suggest the final detachment of the lithospheric slab once subducted all along the Carpathian arc during Miocene to Pliocene times [*Wenzel et al.,* 1998].

In order to understand and quantify the intensity of active deformation in the region the spatial pattern of the total seismic energy release was computed by *Gerner et al.* [1999]. Calculation shows that the most intensely deforming area is

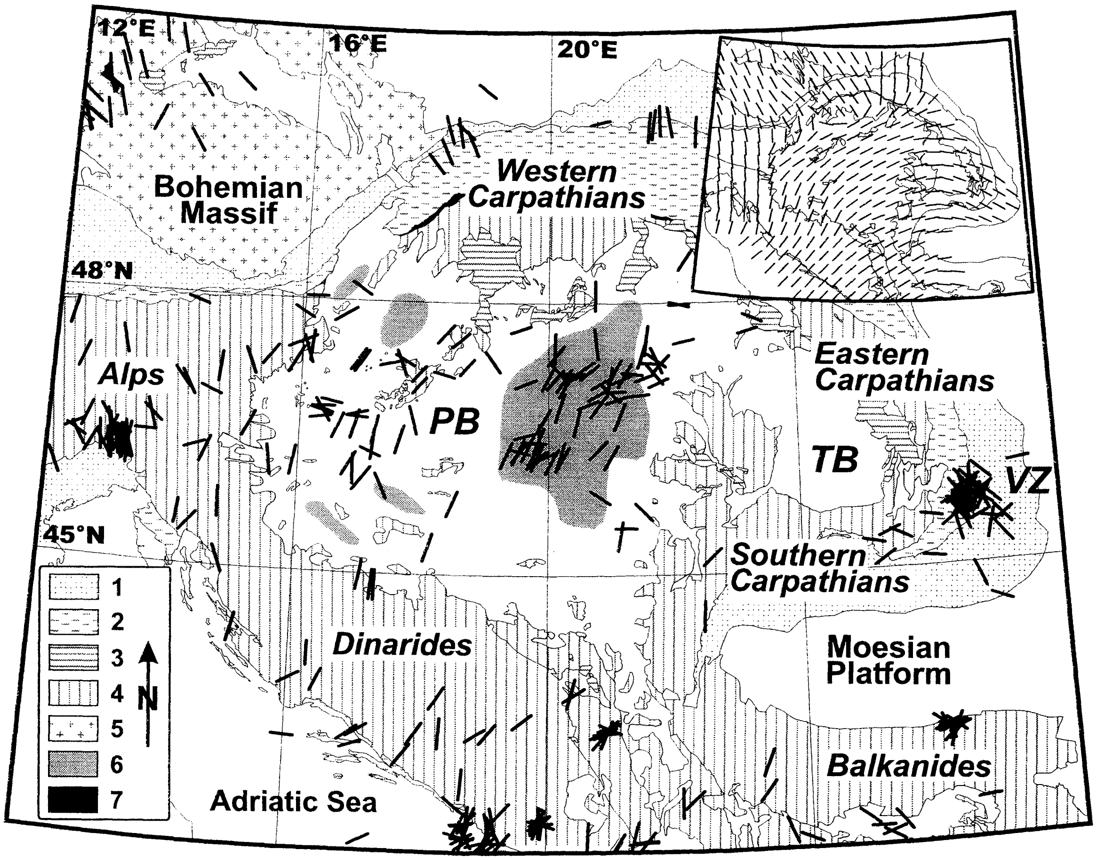

Figure 5. Simplified geological sketch map and maximum horizontal compressive stress orientations S_{Hmax} observed in and around the Pannonian basin by means of earthquake focal mechanism solutions, borehole breakout analysis, and some in situ stress measurements. Inset shows the smoothed directions of maximum horizontal compression obtained by using the smoothing algorithm of *Hansen and Mount* [1990]. 1, foreland molasse belt; 2, Alpine and Carpathian flysch belt; 3, Neogene calc-alkaline vulcanites; 4, pre-Tertiary units of the inner orogens; 5, pre-Alpine Bohemian Massif; 6, areas of accelerated Pliocene-Quaternary subsidence; 7, Pieniny Klippen Belt; PB, Pannonian basin; TB, Transylvanian basin; VZ, Vrancea zone.

the South Alpine - Dinaric chain. This belt exhibits tectonic activity several orders of magnitude higher than any other part of the region. It is interesting to note, however, that seismic energy release in the Pannonian basin is significantly higher than in the surrounding Carpathian arc, where major shortening took place during Miocene and Pliocene times. Furthermore, seismicity data indicate that a higher amount of seismic energy is released in the western part of the Pannonian basin than in the East Alpine orogen itself. These findings suggest that a high level of tectonic stress is concentrated in the upper, i.e., elasto-brittle, layers of the crust underlying the Pannonian basin. Moreover, the hot and thus rheologically weak Pannonian lithosphere [*Lankreijer et al.*, 1999] is a favorable medium to host low- to medium-size earthquakes (M<6) with the absence of larger events due to the dominance of aseismic creep and ductile deformation. Seismic activity does not appear to be restricted to boundaries of large-scale crustal blocks [*Gutdeutsch and Aric*, 1988] but rather to preexisting fault zones with decreased shear resistance.

In order to put constraints on the tectonic style of the late stage (Quaternary) structural development of the Pannonian basin, shallow seismic profiling has been carried out on two main rivers in Hungary (Figure 8) [*Tóth and Horváth*, 1998]. Due to the higher frequency source wavelet and better signal-to-noise ratio, offshore seismic measurements provide at least an order of magnitude higher resolution than standard on-land surveys. Furthermore, the underlying strata are imaged from right below the water bottom, which provides an excellent tool to interpret geological structures from the very top of the sedimentary sequences. The selected seismic profiles (Figure 9 and 10) image a strike-slip fault zone with typical flower structures and en echelon geometry stretching through the central part of the Pannonian basin (Figure 8) [*Tóth and Horváth*, 1998]. The faults on section Danube-207/94, which cut a Pliocene-Miocene sequence beneath Danube River, are sealed with uppermost Pleistocene-Holocene river bed sediments (Figure 9). Thus the stratigraphic hiatus makes it impossible to determine the exact age of fault activation on this profile. However, as evidenced by borehole data and

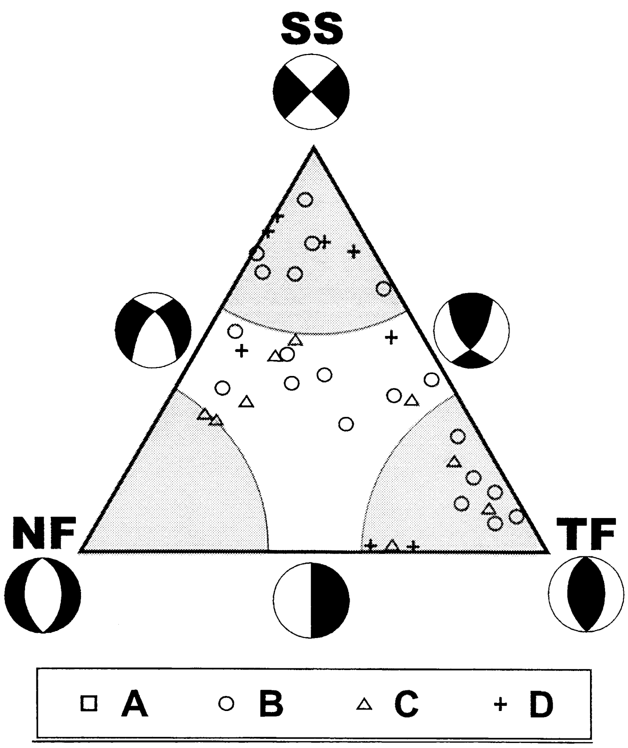

Figure 6. Stress regime within the Pannonian basin reconstructed from the style of faulting during earthquake events. Pure strike-slip faulting (SS), thrust faulting (TF), and normal faulting (NF) are projected to the corners of the triangle, while the solution of mixed components are situated along the borders or inside the triangle [after *Gerner et al.*, 1999]. Letters A through D indicate the quality of focal mechanism determinations (A is best; for quality ranking scheme, see *Zoback* [1992]). The data set evidences the dominance of thrust to strike-slip faulting and that extension has come to an end in the Pannonian basin. The structural inversion of the basin system is in progress.

several on-land seismic sections between the two rivers [*Pogácsás et al.*, 1989; *Lőrincz,* 1997], the same fault zone was imaged beneath Tisza River where active subsidence is taking place and hence the Quaternary strata are far more complete (Figure 10). The profile clearly proves latest Pleistocene fault activity. It is likely that the fault zone is rooted in the pre-Neogene basement [*Pogácsás et al.*, 1989], and it shows recent seismic activity along its central segment near the town of Kecskemét [*Tóth et al.,* 2001]. It is therefore suggested that the fault zone is a presently reactivated geological structure evidencing mainly strike-slip type of upper crustal deformation pattern. The lack of major extensional features along this wrench zone is consistent with other data, suggesting the tectonic inversion of the Pannonian basin.

4. Modeling Method

In order to evaluate gravity-induced stresses in and around an intramountain basin, a finite element analysis has been carried out. The presented plan view models are static and treat the area of interest as a spherical shell with either homogeneous or heterogeneous elastic rheology. Alternative rheologies, such as viscoelastic, are useful for studying how tectonic stresses relax over time. The effect of the rheological stratification of the lithosphere, basal forces exerted at the base of the plates and thermal stresses have been ignored for the purpose of the present study. Although this modeling approach bears several limitations, the present stress study is plausible to seek the first-order regional stress pattern. Since the sources of the first-order stress pattern in the Pannonian basin are renewable (in the sense of *Bott and Kusznir* [1984]) on the geological timescale, they are considered to be in steady state. Therefore, the use of purely elastic rheology appears to be a justifiable simplification for the purpose this study. The area of interest is subdivided into a number of finite elements, being either triangular or quadrilateral in shape, that are interconnected by common nodal points. Since tectonic plates are not accelerating, static equilibrium was assumed and used for numerical calculations. The equilibrium state of the model for a given set of forces and boundary conditions is solved for the displacement of the nodal points and then for the average stress and strain of the finite elements. Plane stress approximation was employed, and the principal horizontal tectonic (i.e., nonhydrostatic) stresses integrated over the thickness of the modeled plate are calculated as modeling output.

The effects of the rheological stratification of the lithosphere, basal forces exerted at the base of the plates, and

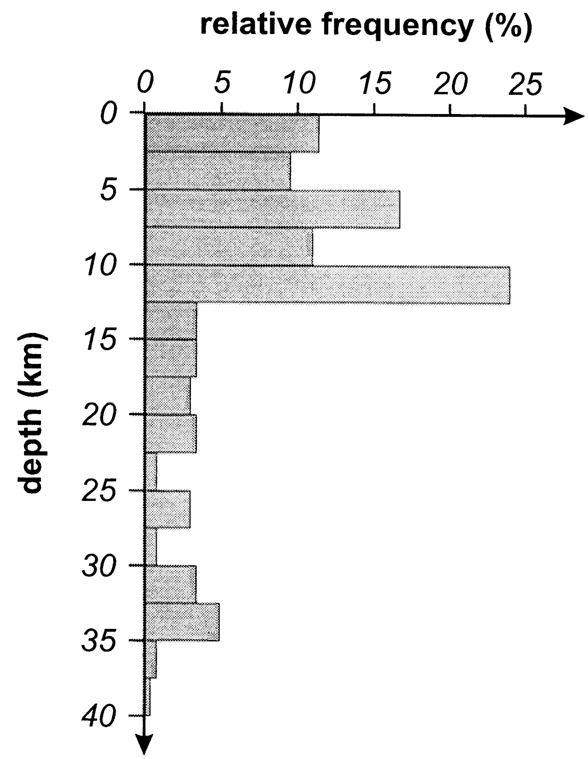

Figure 7. In the Pannonian basin and its surroundings the majority of earthquake hypocenters are restricted to upper crustal levels. The diagram is based on the analysis of the focal depth of 271 events since the year 1928 [after *Tóth et al.*, 2001].

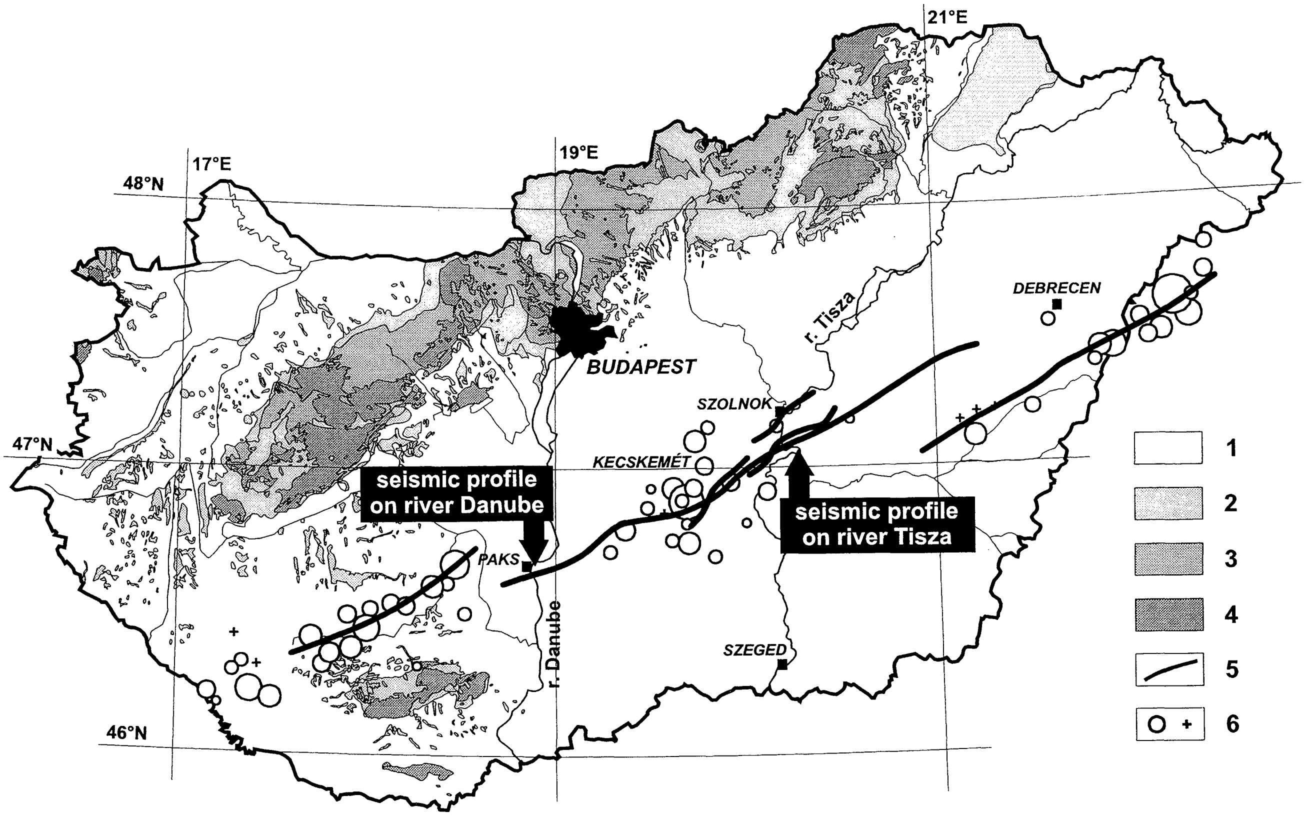

Figure 8. Simplified geological map of Hungary with location of two high-resolution multichannel seismic profiles in the central part of the Pannonian basin. A strike-slip fault zone of late Pleistocene tectonic activity associated with flower structures was imaged beneath Danube and Tisza Rivers. Seismic profiles are shown in Figures 9 and 10. Seismicity pattern along the fault zone is also indicated. 1, Pliocene and Quaternary; 2, Miocene; 3, Paleogene; 4, pre-Tertiary; 5, fault; 6, earthquake epicenters (size of circles is proportional to magnitude).

thermal stresses have been ignored for the purpose of the present study. Although the modeling approach bears several inherited limitations, this stress analysis study is plausible to seek the first-order regional stress pattern.

Potential energy beneath the Earth's surface can be calculated by integrating the buoyancy anomaly over the depth of compensation [*Coblentz et al.,* 1994]. The gravitational potential energy per unit area of a column of rocks P above an equipotential depth z is given by the integral of the vertical stress σ_{zz} from the surface of the Earth to that particular depth:

$$P = \int_h^z \sigma_{zz}(\tau)d\tau = \int_h^z \int_h^\tau \rho(\tau')gd\tau' d\tau,$$

where $\rho(\tau')$ is the density, g is the gravitational acceleration, and τ and τ' are integration variables.

In the presented finite element models, horizontal forces are computed from the gravitational potential energy differences ΔP between any pair of adjacent elements in the model. The related stresses are determined from this P gradient across the elements with the simple equation of $\sigma_{xx} = \Delta P/L$, where L is the thickness of the lithosphere. A calculation scheme was applied [*Coblentz et al.,* 1994] that uses the assumption of local isostatic compensation at the depth of 125 km to calculate the thickness of continental crust and mantle lithosphere associated with the observed topography. Continental lithosphere at sea level was used as the reference lithosphere against which all the considered lithospheric columns are in isostatic balance. The choice of an alternative reference state, e.g., mid-ocean ridges, would result in only minor changes in P estimates [*Jones et al.,* 1996]. To determine density values as a function of depth, the modeled lithosphere is assumed to follow a linear geotherm. The elevation of each node in the finite element mesh was sampled from the ETOPO5 topographic database. Given the topography, the calculated thickness changes of the crust and mantle lithosphere, P variations and the corresponding horizontal forces and stresses can be readily determined. It is noted that the potential energy of continental lithosphere is particularly sensitive to the assumed crustal density. Thus, quantitative estimates of the excess potential energy of regions with high topography are significantly less robust than the estimates of the mean potential energy at the plate and global scale [*Coblentz et al.,* 1994].

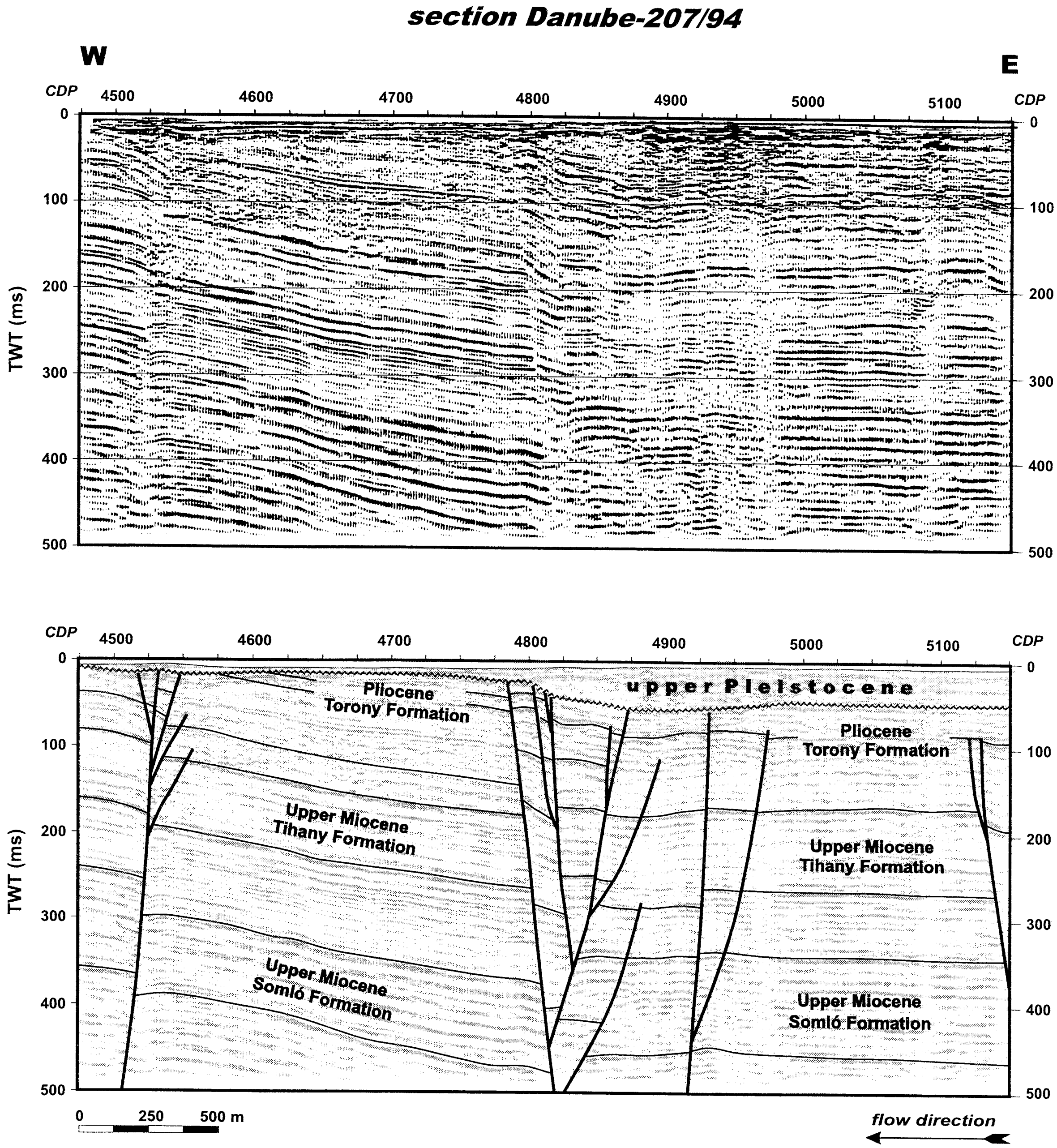

Figure 9. Danube-207/94 high-resolution multichannel seismic section measured at the Paks bend of the Danube River. Interpretation of the profile shows that the Pliocene sequences beneath the Holocene river bed sediments are clearly faulted [after *Tóth et al.*, 1998].

5. Modeling Results

5.1. Two Conceptual Examples

In order to test the modeling approach, simple models have been developed to examine the effect of elevated topography on the stress pattern in a nearby basin. The modeled area is treated as a homogeneous elastic plate with a uniform Young's modulus of E = 75 GPa and Poisson's ratio of ν = 0.25.

In model set 1, the top of the basin is constantly kept at sea level, whereas the neighboring mountain belt is elevated by 1, 2, and 3 km (Figure 11a). The slope at the transition zone is very gentle, i.e., <1° in all cases. A uniform pate thickness of 100 km was employed, and an average surface density of ρ = 2850 kg/m^3 was chosen for the entire model. The highland area is characterized by an excess of potential energy relative to the adjacent basin and is under net tension. In contrast, the lithosphere of the lowland basin exhibits a defect of

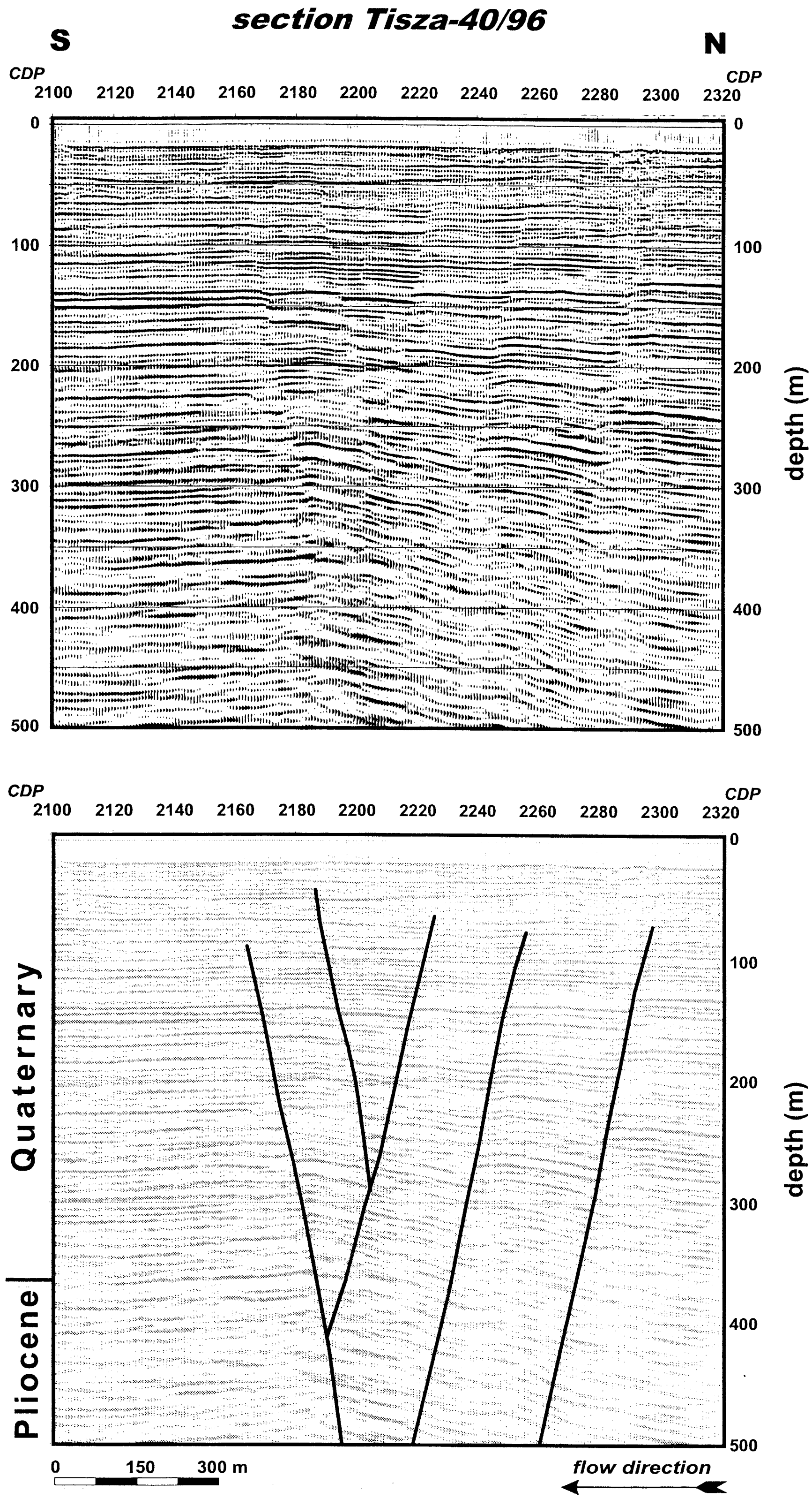

Figure 10. Tisza-40/96 high-resolution multichannel seismic section measured on the Tisza River south of Szolnok. Interpretation of the profile clearly shows that the Pleistocene sequences up to the depth of 45 m are faulted (flower structure), which suggests latest Pleistocene activity of this strike-slip fault zone [after *Tóth et al.*, 1998].

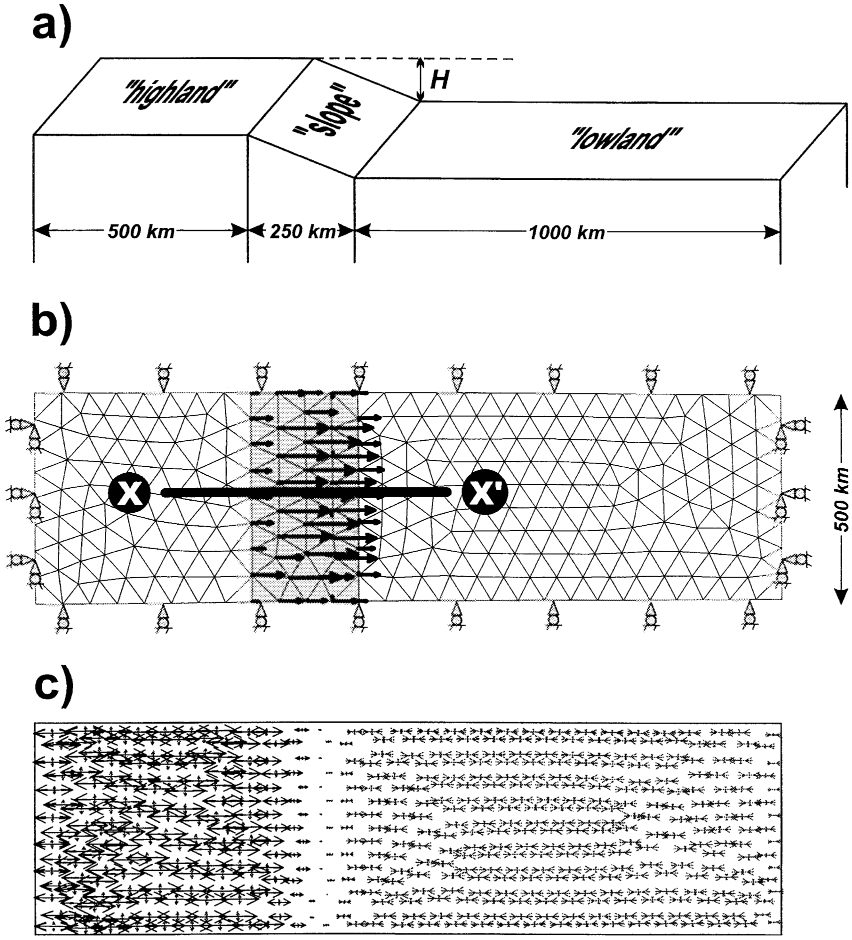

Figure 11. (a) Geometry of the model that explores the effect of elevated topography on the stress pattern of an adjacent basin. Three cases are invesitgated where the elevation of the highland region H is 1, 2, and 3 km. (b) Finite element mesh of the models in plan view. Arrows in the vicinity of the slope region indicate nodal forces induced by the potential energy differences between adjacent nodes. Nodes along the longer sides of the model are constrained in the direction parallel to the strike of the slope, while nodes are completely fixed along the shorter edges. A uniform plate thickness of 100 km was employed. The calculated stress magnitudes along transect X-X' are shown in Figure 12. (c) Calculated direction of in-plane stress axes. Outward pointing black arrows depict tension (highland region); inward pointing shaded arrows represent compression (basin area).

gravitational potential energy. Hence the gradient of potential energy between the two regions produces forces pointing toward the basin area (Figure 11b). Because the edges of the modeled elastic plate are fixed, the lowland is under net compression. Owing to the very simple geometry of the model the orientation of tension and compression in the highland and lowland, respectively, is everywhere parallel to the dip of the transition zone (Figure 11c). The calculated stress magnitudes are proportional to the altitude differences. When the elevation contrast varies from 1 to 3 km, the magnitude of tension increases from about ~6 to 22 MPa in the mountain, whereas the magnitude of compression increases from 3 to 12 MPa in the basin (Figure 12).

In model set 2, the effects of the presence of water and sediments in a basin are investigated (Figure 13). Elastic parameters are as in model set 1. The geometry of the model is kept constant, and the slope between the plateau and the basin is now somewhat steeper. The only difference between the three models is the basin fill, i.e., it is filled up by air, water, and light sediments in models A, B, and C, respectively. In all cases, the bottom of the basin is at 1 km below sea level (Figure 13a). The resultant stress pattern is very similar to that in the previous model set (Figure 13b). The magnitude of compression in the basin is decreasing from 6 to 4 MPa as it is filled up with water and to ~3 MPa when water is replaced by soft sediments with an average density of 2000 kg/m^3 (Figure 14). A similar trend is calculated for the magnitude ranges of tension in the plateau area. Obviously, when the density of the material constituting the basin fill is converging to that of the basement, the potential energy differences and hence the magnitude of the induced stresses will decrease.

Results of these simple conceptual models suggest that forces related to changes of topography and associated density

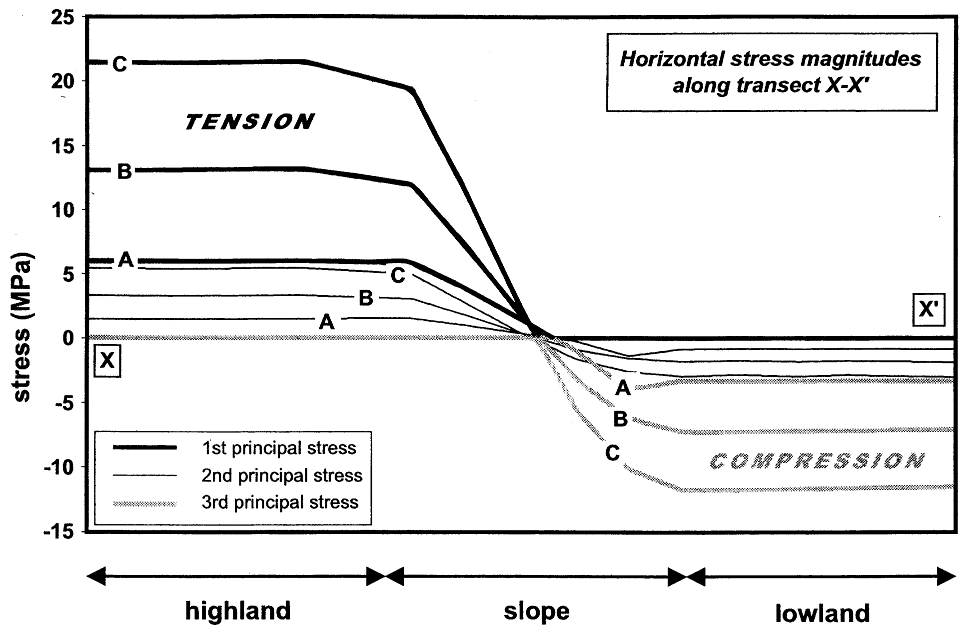

Figure 12. In-plane stress magnitudes calculated for the model shown in Figure 11. Since plane stress approximation was applied, the magnitude of one of the three principal stress is always zero. Note that positive values in the plateau region (highland) indicate tension, whereas negative values denote compressional stresses in the basin (lowland) area. A, B, and C mark topography elevated by 1, 2, and 3 km, respectively, above the basin floor.

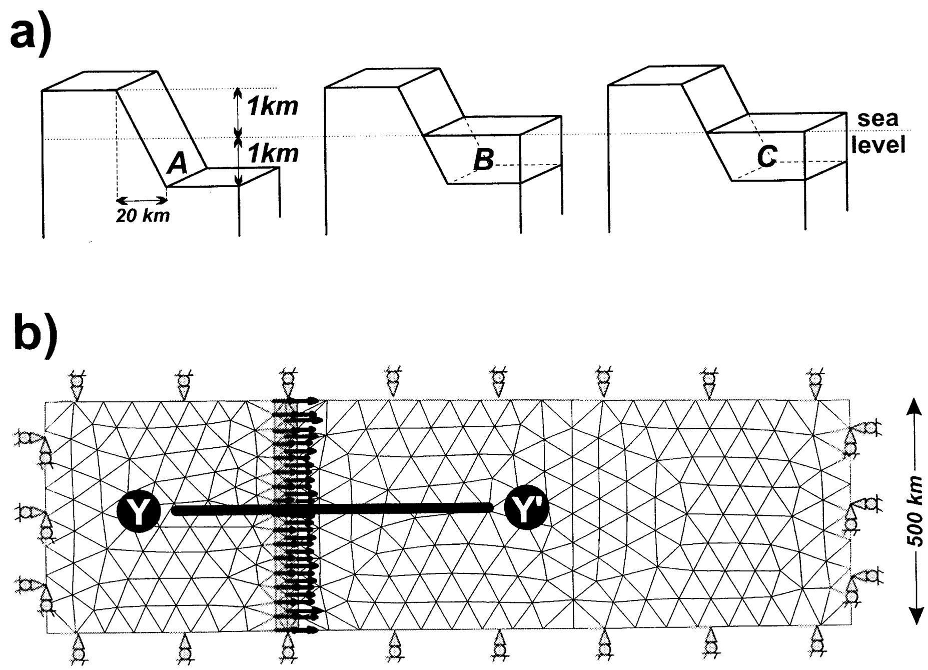

Figure 13. (a) Geometry of the model designed to analyze the effect of an elevated topography above a basin filled up by air (case A), water (case B), and light sediments (case C). The plateau is elevated by 1 km above sea level, while the basin floor is at the depth of 1 km below sea level. Figure 13a is strongly exaggerated in the vertical direction. The dip angle of the slope region is much larger compared to the previous models. (b) Finite element mesh of the models in plan view. Arrows indicate nodal forces induced by the potential energy differences between the adjacent nodes in the vicinity of the slope region. Side nodes along the longer sides of the model are again constrained in the direction parallel to the strike of the slope, whereas nodes are completely fixed along the shorter edges. The computed stress magnitudes along transect Y-Y' can be see in Figure 14.

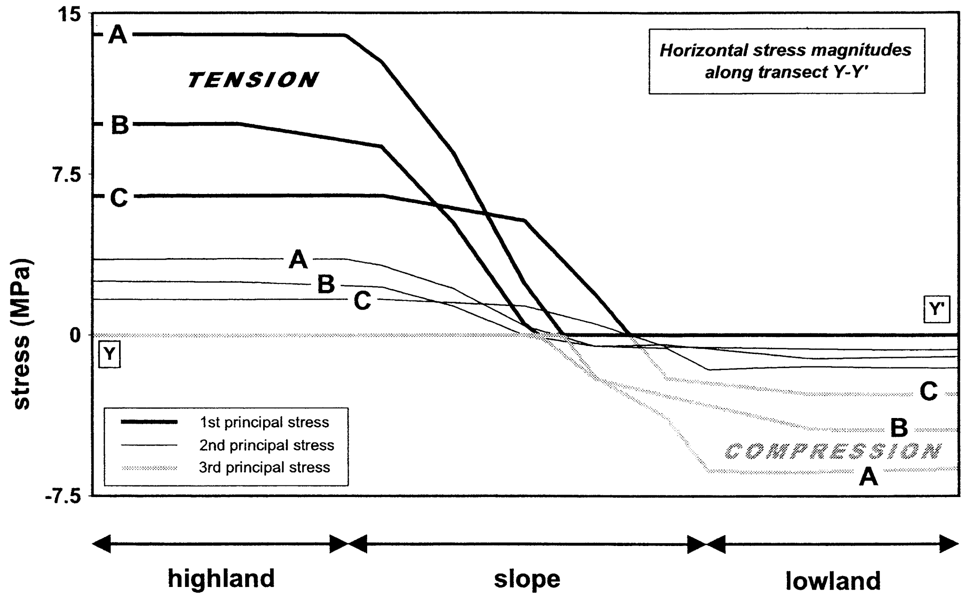

Figure 14. Calculated stress magnitudes in the internal parts of the second model set shown in Figure 13. Positive values in the plateau region indicate tension, whereas negative stress magnitudes (compression) are characteristic for the basin area. Letters A, B, and C and transect Y-Y' refer to the model setup depicted in Figure 13.

anomalies are capable of producing stresses with magnitudes similar to those of tectonic origin. Particularly, gravitational stresses are likely to play a key role when sedimentary basins are evolving in a zone of active orogeny in the immediate vicinity of elevated mountain belts. In addition to the far-field stresses generated by collisional forces, compressional stresses due to topography-induced gravitational stresses can make a major contribution to the structural development of intramountain sedimentary basins. Building on this finding, the section 5.2 explores the late stage tectonic inversion of the Pannonian basin from the viewpoint of the interaction of various stress sources effecting the region.

5.2. Stress Models for the Pannonian Basin

In this part we attempt to quantify tectonic and gravity forces and stresses in and around the actively deforming Pannonian basin. Model boundaries were defined as the northern border of the Eastern Alps, the front of the Carpathian flysch belt, and the contact of the Adriatic unit and the Dinarides (see Figure 4). These boundaries correspond to the external limits of the tectonic units of the Alpine-Carpathian orogen. The area of interest is treated as a spherical shell and is subdivided into 1650 triangle elements; the average size of the element edges is about ~20 km. Boundary conditions are applied either as zero displacements along nondeforming edges or by loads utilized as tectonic line forces acting along actively deforming model boundaries.

First, the effect of the irregular topography and related crustal thickness variation in the Pannonian region is examined separately (Figure 15). As a simple reference, the area of interest was assigned with a plate thickness of 100 km, while all model edges were fixed perpendicular to their strike. This model configuration, i.e., the lack of forces other than those arising from topographic effects, is an obvious oversimplification of the present-day geodynamics of the Pannonian basin system. However, it is useful for gaining insight into the nature and magnitude of stresses associated with such forces. Calculations show that elevated areas are characterized by pure horizontal tension (Figure 15a). The maximum tensional stress axes are, as one can expect, parallel to the local topographic gradient. In simple words, the high mountains tend to spread under their own weight. In the Alps and Dinarides the magnitude of tension can locally reach up to 10 MPa averaged over a 100 km thick lithosphere (Figure 15b). In contrast, the interior of the Pannonian basin is under net horizontal compression with magnitudes generally <10 MPa. These results, in good accordance with the above described theoretical examples, suggest that in the absence of tectonic forces many flat-lying and low-altitude sedimentary basins surrounded by mountain belts would be under compression. Due to the lack of plate thickness variation in this model, however, the calculated stress magnitudes represent only rough estimates.

In the second model, gravitational forces were combined with other stress sources, and more realistic elastic thickness values were assigned to the Pannonian lithosphere (Figure 16). Plate boundary forces associated with the ongoing convergence of the European and Adriatic plates [*Anderson and Jackson,* 1987; *Ward,* 1994], the effect of the western European stress province [*Müller et al.,* 1992], and the slab detachment process at the SE Carpathians [*Fan et al.,* 1998; *Wenzel et al.,* 1998] were added, and their combined effect with gravity forces was determined.

The push associated with the counterclockwise rotation of the Adriatic microplate [*Anderson and Jackson,* 1987; *Ward,* 1994; *Bada et al.,* 1999] was applied as a line force acting

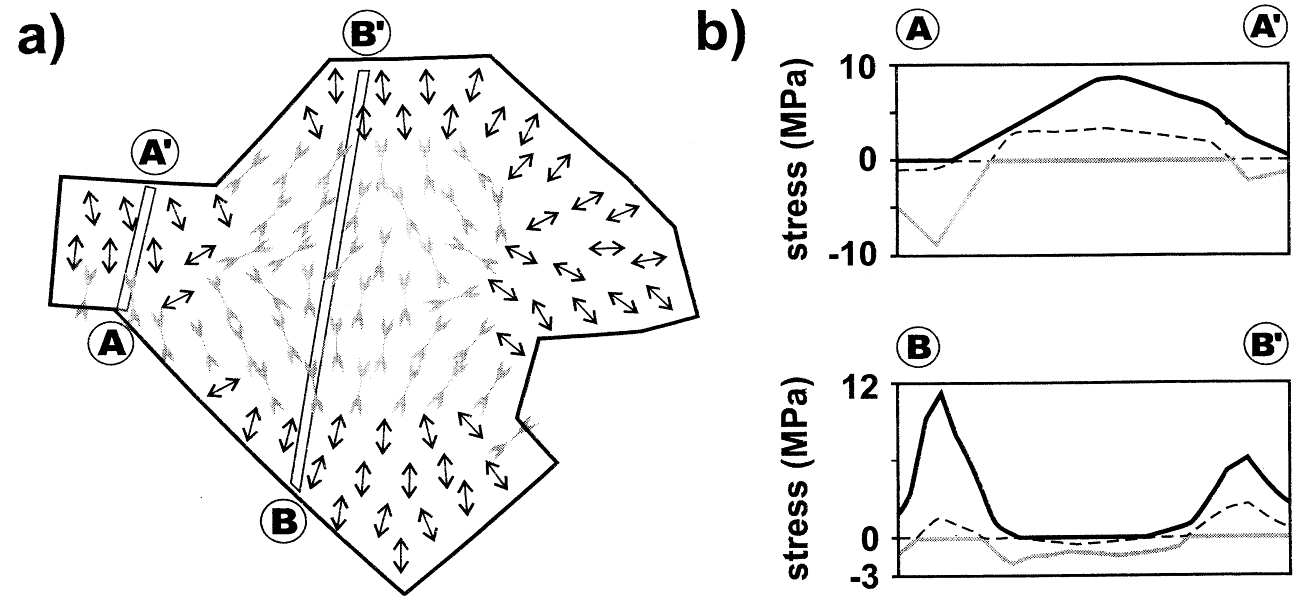

Figure 15. Model geometry and results showing the effect of gravitational forces due to topography variation in the Pannonian region. (a) In the absence of other stress sources, topographic forces induce net tension in the elevated areas (outward pointing black arrows at selected elements), whereas the basin interior is characterized by slight compression with axes perpendicular to the strike of the neighboring mountain chain (inward pointing shaded arrows at selected elements). (b) In-plane stress magnitudes along two transects through the eastern Alps (A-A') and the Dinarides and Pannonian basin and western Carpathians (B-B'; for location of sections see Figure 4). Solid, dashed, and shaded lines denote first, second, and third principal stress magnitudes, respectively. The calculated stresses are averaged over a 100 km thick elastic lithosphere. Note that, since plane stress approximation is adopted, vertical stresses are always zero. Positive values denote tension.

perpendicular to the Alpine and Dinaric front ("Adria push") (Figure 16a). To represent the rotation, the magnitude of this force was linearly increased toward the southeast along the Adriatic coastline. The effect of the western European stress province and the active push at the Vrancea zone ("Vrancea push"), which is assumed to be related to the final detachment of a once subducting slab along the entire Carpathians [*Wenzel et al.*, 1998], were also treated as linear forces perpendicular to the edges at the western and easternmost Carpathians, respectively. To simulate the lower rheological strength of the interior Pannonian basin, elements with reduced Young's modules were used to represent this region. The modeled plate had a nonuniform thickness simulating the variation of effective elastic thickness (EET) in the region obtained from rheological model calculations [*Lankreijer,* 1998]. Minimum EET values (10 km) were used in the case of the central part of the Pannonian basin, whereas this value was gradually increased to a maximum of 25 km toward the peripheral mountainous areas. Once the nodal forces due to topographic effects are determined, the above described set of forces can be fine-tuned until a satisfactory fit between the observed and computed stress pattern is obtained. This way the topographic forces were the invariables during the calculation and served as a basis for the calibration of the direction and magnitude of other forces. We found that the best fit can be attained when the magnitude of Adria push is increasing from ~3×10^{12} to 5×10^{12} N/m along the Adriatic coast, which corresponds to a tectonic stress of 30-50 MPa averaged over a 100 km thick lithosphere [see also *Gölke and Coblentz,* 1996]. Forces from the Vrancea zone and the Bohemian Massif appear to be of secondary importance with a maximum magnitude slightly less than 1×10^{12} N/m. The fan-like pattern of the calculated horizontal compression in the central part of the Pannonian basin and NE-SW directed compression in its western sectors are very close to the observed stress directions (Figure 16a). Local compression with NW-SE oriented S_{Hmax} is calculated for the Vrancea zone. In the absence of Vrancea push, this area would experience net tension perpendicular to the mountain belt.

The following generalization can be put forward on these modeling results. Clearly, the whole Pannonian region is under compression, and the applied set of forces can induce stresses as high as >100 MPa in the southwestern part of the Pannonian basin and in the vicinity of the Moesian Platform (Figure 16b). The calculated stress values are in the same range with the stress magnitudes obtained by the results of hydrofracture experiments at a depth of 3.3 km in the center of the Pannonian basin [*Gerner et al.,* 1999]. It has been found that the magnitude of minimum principal stress σ_3 corresponds to the weight of the overburden, whereas σ_1 was horizontal with maximum magnitude of ~200 MPa. In contrast, the most elevated areas in the eastern Alps and the eastern Carpathians show very reduced compressional stresses. This suggests that at altitudes higher than 3000 m

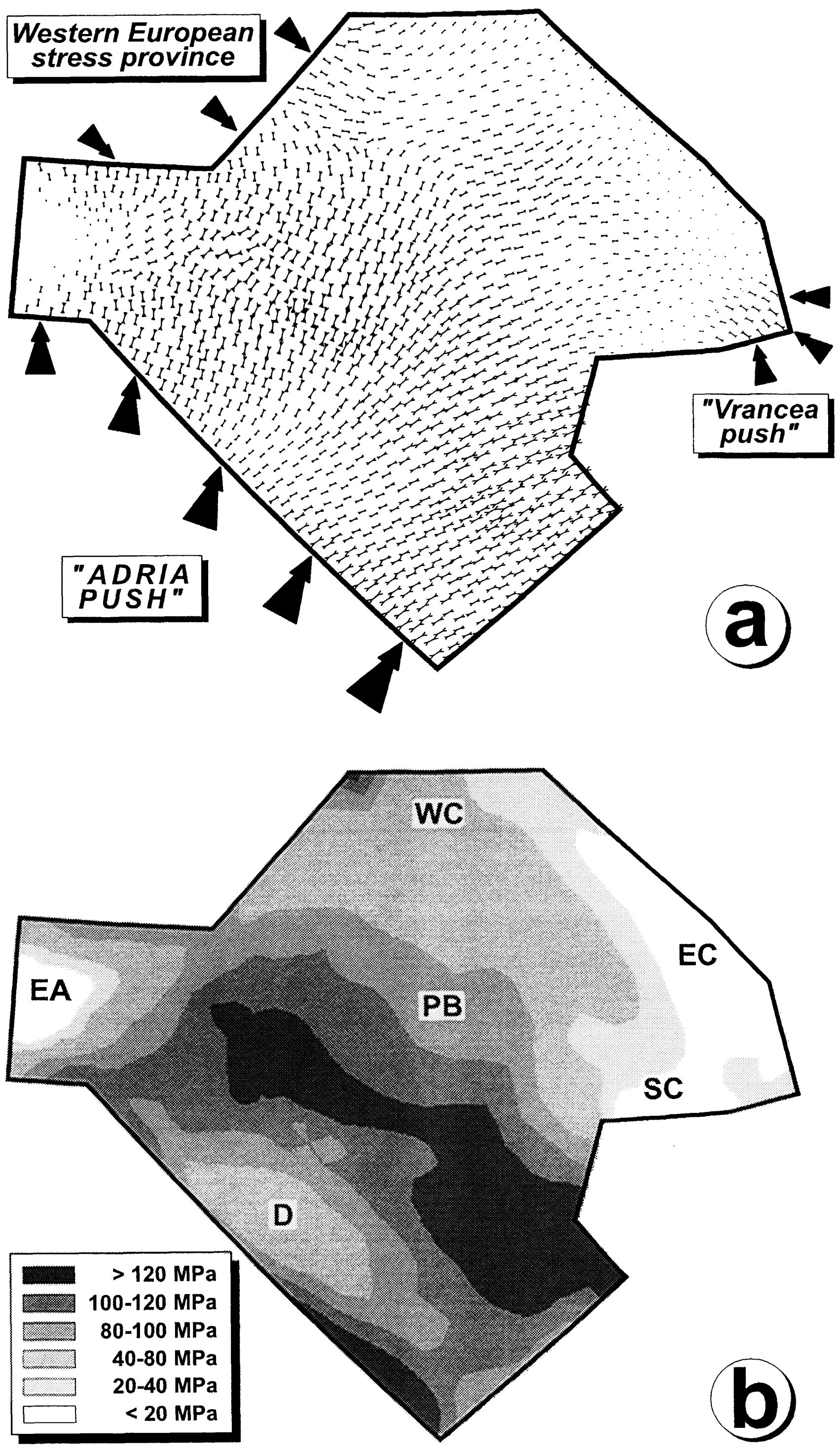

Figure 16. Modeling results revealing the combined effect of gravitational and external tectonic forces. (a) Arrows indicate the orientation of maximum horizontal compression. In the western sectors of the Pannonian basin, the elevated topography of the Eastern Alps has a profound effect on the stress pattern, i.e., compression becomes NE-SW oriented. (b) Magnitude of the calculated in-plane maximum compressive stresses. Increased stresses are concentrated in the southern part of the modeled area that leads to intense deformation in the vicinity of the Dinaric belt manifested in a high level of seismicity. D, Dinarides; EA, eastern Alps; EC, eastern Carpathians; PB, Pannonian basin; SC, southern Carpathians; WC, western Carpathians.

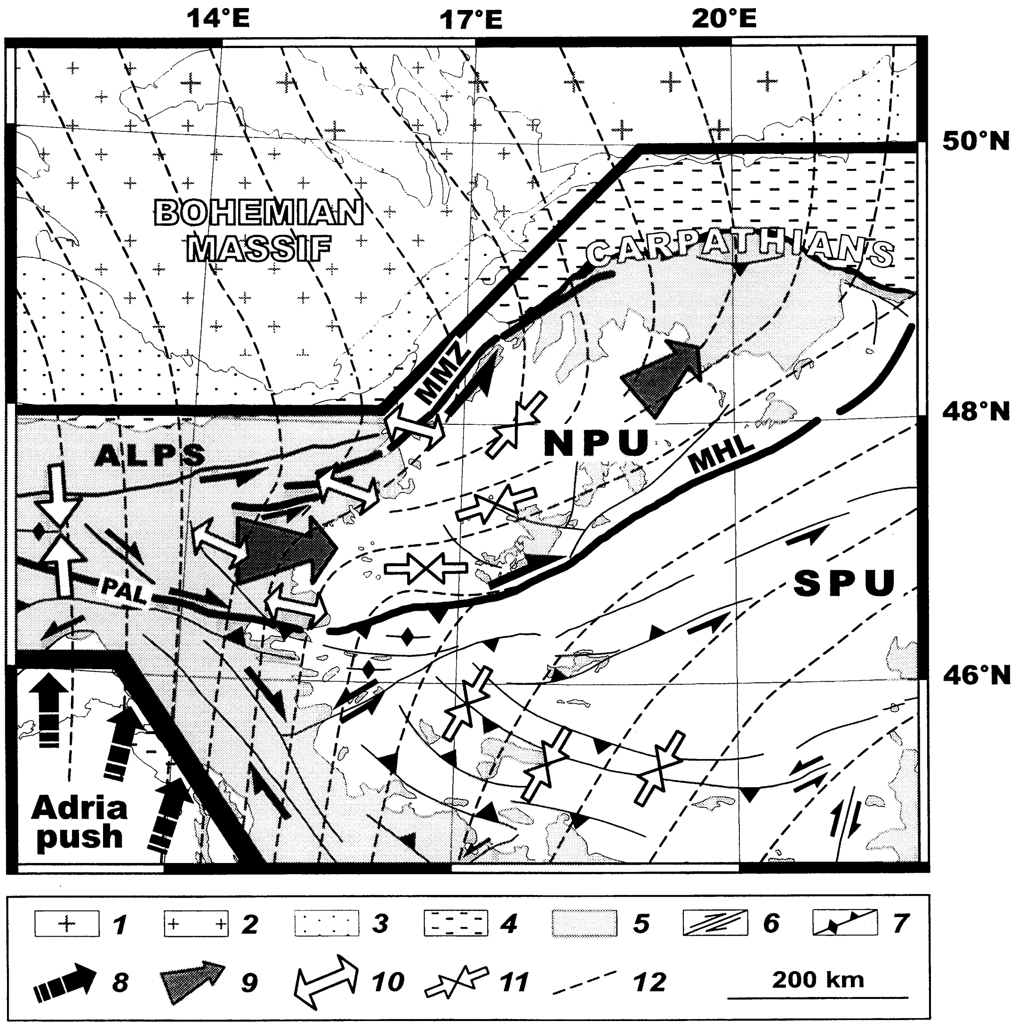

Figure 17. Cartoon summarizing the main features of the recent tectonic pattern in the western part of Pannonian basin system. Maximum horizontal stress directions are controlled by the interplay of collisional forces related to the indentation of the Adriatic microplate (Adria push) and gravitational forces associated with the elevated topography of the Alpine orogenic belt. The effect of buoyancy stresses is particularly important at the contact zone of the Alps and the Pannonian basin. Owing to the weak rheology of the Pannonian lithosphere and the boundary conditions inherent in this dynamic system, crustal wedges are currently expelled from the axial zone of the Alpine collision zone toward the east-northeast. NPU, North Pannonian unit; SPU, South Pannonian unit; MHL, Mid-Hungarian lineament; MMZ, Mur-Mürz-Žilina line; PAL, Periadriatic line. 1, European platform; 2, Bohemian Massif; 3, molasse belt; 4, flysch belt; 5, internal pre-Tertiary units; 6, strike-slip fault; 7, anticline and reverse fault; 8, drift of Adria; 9, material transport direction in NPU; 10, local tension; 11, local compression; 12, trajectory of S_{Hmax}.

above sea level the state of stress can be tensional even in collisional settings [e.g., *Richardson and Coblentz,* 1994].

6. Discussion

6.1. Role of Buoyancy Forces in Basin Inversion: The Example of the Western Pannonian Basin

As has long been recognized, long-term deformation processes can significantly alter the density distribution through crustal and lithospheric thinning or thickening and corresponding changes in surface elevation. Owing to the significant short-scale variation of the density structure of the lithosphere in zones of active orogeny, the gravitational potential energy P can exhibit rapid spatial and temporal changes. Differences in P values will result in differences of the state of stress through neighboring lithospheric columns. As a rule of thumb, the excess of P, often associated with elevated mountain ranges and related increase of crustal thickness, can lead to the development of tensional stresses. In contrast, subsided regions with attenuated crust are usually characterized by low P values. Consequently, as pointed out by several authors [e.g., *Fleitout and Froidevaux,* 1982; *Bott,* 1990; *Richardson and Coblentz,* 1994], a thickened and elevated orogenic wedge can exert significant compressional forces onto its flat-laying environment when no other forces are counteracting these body forces. Sedimentary basins are very often prone to tectonic reactivation subsequent to synrift evolution due to the decreased rheological strength of the heated underlying lithosphere. The presented conceptual models indicate that, depending on the altitude difference, compressional stresses in the order of 5-10 MPa, averaged over a 100 km thick lithosphere, are induced in sedimentary basins adjacent to an elevated mountain range. These stress magnitudes, especially when amplified and concentrated in the higher, elasto-brittle lithospheric levels by creep processes [*Kusznir,* 1982], appear to be capable of triggering and sustaining deformation rates of tectonic significance. When external forces causing stretching and extension in basins cease, compressional stresses may take control on the deformation pattern. Depending on local circumstances, compressional basin inversion can be initiated either by far-field or buoyancy forces. In the case of the western European foreland the present-day stress field is governed by the combined effect of plate boundary (Africa-Europe convergence) and gravitational (Atlantic ridge push) forces [*Gölke and Coblentz,* 1996; *Ziegler et al.,* 1998]. Within zones of active collision, where intense convergence results in highly irregular topography, the relative importance of these processes may change abruptly in both time and space.

To explain the observed stress and strain pattern in the Pannonian basin, *Bada et al.* [1998] put forward a simplified model in which plate boundary forces played an exclusive role and buoyancy forces associated with surface undulation and lithospheric density variation were neglected. However, our modeling results suggest that these forces can significantly influence the state of stress and hence may have imprint on the present-day deformation pattern. Collisional forces associated with the Adria-Europe convergence and topographic forces associated with the uplifted Eastern Alps mutually control the present-day stress and strain pattern in the western part of the Pannonian basin system. As evidenced by the seismicity pattern [*Gerner et al.,* 1999] and confirmed by recent GPS measurements [*Grenerczy et al.,* 2000], this elevated area of the thickened Alpine crustal wedge is presently moving eastward toward the interior of the Pannonian basin. A plausible mechanism for such deformation in collisional settings is the lateral extrusion of crustal blocks that can occur as a result of a lateral pressure gradient pointing out from regions of high topography and thick continental crust [cf. *Bird,* 1991]. This gradient of the gravitational potential energy can trigger ductile flow especially in weakened layers of the lithosphere. Given the elevated topography in the axial zone of Alpine collision and, moreover, a buffering foreland of extremely high strength represented by the Bohemian Massif, crustal fragments can spread only toward the lowland region of the weak Pannonian lithosphere. The East Alpine orogen itself is also characterized by low integrated strength due to the great thickness of the crust and hence its high heat production. Since subduction has been fully terminated along the Alpine-Carpathian chain, the termination of slab retreat provides no further space for lithospheric extension in the internal basin area. The absence of trench suction forces once associated with slab retreat results in the dominance of compressional intraplate stresses related to the interaction of collisional and gravitational forces. The northern and eastern edges of the laterally constrained Carpathian embayment restricts further extension and hinders material transport into the Pannonian basin. Consequently, parallel with the complete termination of subduction along the Carpathian arc, extension is no longer prevailing in the region. Instead, as demonstrated by recent stress data and modeling results, a high level of compressional stress is concentrated in the elastic core of the lithosphere. Moreover, this geodynamic setting can well explain the gradual inversion of the intra-Carpathian area manifested in late stage subsidence anomalies, i.e., accelerated subsidence in, e.g., the Danube basin and the Great Hungarian Plain and uplift of Transdanubia (see Figure 5), associated with an increase of intraplate compressional stresses. Thus, in accordance with predictions [*Horváth and Cloetingh,* 1996], we suggest that the Pannonian region is currently in a state of positive structural inversion, which is at least partly due to the elevated topography around the basin system, especially in its western part.

6.2. Stress Regime, Stress Magnitudes, and Style of Deformation in the Pannonian Basin

Numerical models predict that collisional forces associated with the counterclockwise rotation of the Adriatic microplate exert a primary control on the state of stress in the Pannonian basin (Figures 16 and 17). As a consequence of Adria push, compression is induced at the northern and eastern Adriatic coastline, which is manifested in the high level of seismicity in the Southern Alps and Dinarides. The trends of the western European stress province with NW-SE oriented S_{Hmax} [*Müller et al.,* 1992] appear to have a visible expression only at the northwestern region of the study area, close to the Alpine-Carpathian junction. Over a relatively small distance toward the south, this direction rotates nearly 90°; that is in the western Pannonian basin stress indicators are aligned in NE-SW to E-W direction. Modeling results suggest that this pattern is due to the effect of the elevated topography of the nearby eastern Alps giving rise to significant (up to 60°-90°) stress deviation in this area (Figure 17). In accordance with the findings of *Sassi and Faure* [1997], abrupt spatial changes in the stress field are often related to the occurrence of large-scale faults and detachment zones. Thus, the presence of a major structural discontinuity, the Periadriatic – Mid-Hungarian shear zone, may further enhance mechanical decoupling of adjacent tectonic units. As suggested by *Windhoffer* [2000], the close vicinity (~20 km) of orthogonal S_{Hmax} directions measured north and south of the Mid-Hungarian lineament may be partly explained by the presence of a crustal-scale mechanical inhomogeneity with reduced frictional resistance.

It appears that forces associated with elevated topography have important influence on both the magnitude and the orientation of the state of stress in the Alpine collisional belt and intramountain basins. This is supported by model predictions, which show that most elevated areas in the eastern Alps are characterized by reduced compression and a near-tensional state of stress. Tensional stresses may eventually overcome collisional forces acting from the south. In the eastern Alps this is indicated by the late stage transient orogen-perpendicular extension of probably Quaternary age [*Peresson and Decker,* 1997]. Small Quaternary grabens of transtensional origin indicate similar transient extension in the elevated areas of the bending southeastern Carpathians near the Vrancea zone [*Ciulavu,* 1999].

Recent stress data indicate that the present-day stress regime in especially the western parts of the Pannonian region is predominantly strike-slip or compressive. Numerical models predict large compressive stresses in the southwestern areas (>100 MPa) that are concentrated in the thin (<10 km) elastic core of the hot (i.e., weak) lithosphere beneath the Pannonian basin. The estimated stress magnitudes are close to or slightly exceed the integrated lithospheric strength of the Pannonian lithosphere calculated by *Lankreijer* [1998]. Seismicity pattern indicates brittle failure dominantly at microseismic level. Besides brittle faulting, stresses are thought to relax through two dominant mechanisms: to a large extent by aseismic creep [*Gerner et al.,* 1999] and whole-lithosphere buckling [*Horváth and Cloetingh,* 1996; *Cloetingh et al.,* 1999]. On the other hand, the similar level of stress in the much colder and thus stronger Dinarides is more likely manifested in shear rupturing or reactivation of preexisting fractures. Accordingly, the dominant style of the observed deformation in this region is brittle faulting at macroseismic level. Interestingly, the spatial pattern of the total seismic energy release [*Gerner et al.,* 1999] suggests that with the exception of the Dinarides and the Vrancea zone, considerably more intense deformation is taking place in the Pannonian basin than in the surrounding orogenic belts.

Owing to the convergence between the Adriatic plate and the Bohemian Massif and the presence of a weak eastern interface toward the Pannonian basin, crustal wedges are currently squeezed out from the region of the Eastern Alps (Figure 17). These units are moving eastward along major strike-slip fault systems, the sinistral Mur-Mürz-Žilina [*Decker and Peresson,* 1999] and the dextral Periadriatic-Mid-Hungarian fault system [*Fodor et al.,* 1998; *Vrabec,* 1999] in the north and south, respectively. Pure thrusting or thrusting with dextral component (transpression) was observed along several fault zones in the Dinarides [*Del Ben et al.,* 1991]. Confirmed by the results of numerical modeling and seismological data, the observed deformation pattern, close to plate boundary, is clearly associated with and controlled by the N-NNW drifting and counterclockwise rotation of the Adriatic microplate relative to Europe. This is further evidenced by the results of space geodesy. On the basis of very long baseline interferometry data it was concluded [*Ward,* 1994] that the Adriatic crustal block is rotating in a counterclockwise manner with respect to Europe and this rotation results in an intense indentation into the South Alpine-Dinaric orogenic belt.

7. Conclusions

The finite element models presented in this study analyzed the interplay between tectonic and gravitational forces in zones of active collision with highly irregular topography. It has been shown that in the absence of tectonic forces, sedimentary basins surrounded by elevated mountain belts would experience net horizontal compression. Forces associated with changes of topography and associated density anomalies are capable of producing stresses with magnitudes similar to those of tectonic origin. In addition to the tectonic stresses generated by far-field collisional forces, compressional stresses due to topography-induced gravitational forces can make a major contribution to the structural development of intramountain sedimentary basins. When, for some reason, external forces producing extensional deformation in a back arc setting vanish, the resultant compressive stress field can lead to the termination of lithospheric extension and, eventually, give rise to the gradual late stage inversion of the basin system.

Our model calculations suggest that the recent, predominantly strike-slip to compressive stress regime in the Pannonian basin is primarily controlled by the northward drift and counterclockwise rotation of the Adriatic microplate (Adria push). Consequently, this crustal block of relatively high strength is actively indenting and pressing the Pannonian lithosphere against its rigid foreland, the Polish and East European Platforms. However, it was also found that gravity forces associated with elevated topography and related crustal thickness variation of the mountain belt around the Pannonian basin induce horizontal compression, locally exceeding the magnitude of the far-field tectonic stresses. Thus we conclude that the inversion of the western part of the Pannonian basin is partly due to the topographic effect of the adjacent Alpine mountain belt. With the aid of the gravitational stresses, we predict that a high level of compressive (up to >100 MPa) stress is concentrated in the thinned Pannonian lithosphere. This stress magnitude, close to the yield limit, appears to be efficient to cause large-scale folding of the thermally weakened lithosphere beneath the Pannonian basin system.

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